Field testing and CFD LES simulation of offshore wind flows over coastal dune terrain in Northern Ireland.

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ABSTRACT: The role of offshore-directed winds in aeolian sand transport over and along coastal dune systems is studied under a project funded through the UK's Natural Environment Research Council (NERC) "Responsive Mode Program". The field study area is a 6km beach located at Magilligan Strand, Northern Ireland. The coastline has a northeastern-facing orientation on the margin of the Atlantic Ocean and forms the seaward edge of a large vegetated Holocene (5-6000 yrs BP) cuspate foreland. Landward of the beach/foredune crest, a series of 15-20m high vegetated dune ridges are located parallel to the shore. A component of this research program is the measurement of the wind flows over and across the dune and beach terrain and comparison with Computational Fluid Dynamic simulation results Detailed wind flow measurements were obtained during field testing in September 2009 using an extensive array of mast mounted three-dimensional ultrasonic anemometers. Large Eddy Simulation (LES) was performed of the wind flow over the terrain using the open-source CFD software OpenFOAM. The computational domain and mesh includes the terrain obtained by high resolution LIDAR measurements with localized mesh refinement near the complex terrain. The paper illustrates the comparison between the measured and simulated wind flow characteristics. The discussion also includes early commentary on how the new insights into the windflow characteristic inform study of the evolution of coastal dune geomorphology.

1 INTRODUCTION

The existence of extensive aeolian dunes on coasts where the dominant wind direction is offshore is difficult to explain within the traditional assumptions of foredune morphodynamics. Often, regional shifts in wind regime are invoked to explain their development. Previously Hesp (2005) suggested that 'topographic steering' of the wind field through modification of wind velocity by pre-existing topography resulting in a flow reversal, was the dominant mechanism in the development of climbing dunes on a leeside coast in New Zealand. The existence of such flow reversal under offshore winds has recently been identified by Walker *et al*. (2006), but was regarded by those authors as unimportant in sediment transport dynamics at that site. Recent work by Lynch *et al*. (2008, 2009) however, is the first to measure (rather than simply infer) landward Aeolian sediment transport associated with local topographic steering of offshore directed airflow. A principal component of sediment budget analysis in a terrestrial beach and foredune environment is the identification of significant wind events capable of aeolian transport of sediment over various spatial and temporal scales (Anthony *et al*., 2007). In previous studies, offshore winds have received limited attention in sediment budget analyses (e.g. Illenberger and Rust, 1988).

Atmospheric boundary layer flows, and those occurring over complex terrain, remain challenging to accurately reproduce in both physical (wind tunnel) and computational models. Numerous CFD studies of wind flows over complex terrain have been performed to evaluate the performance of different modeling strategies, especially the ability of turbulence models to predict the measured behavior of the accelerating and separating flow in three dimensional terrains. Much of the work to date has been two-dimensional, Jackson and Hunt (1975), Byrne and Holdo (1998), Abe et al. (1993), Nicholas (2001), Safarzadeh et al. (2009), Parsons et al. (2002). Most found significant disagreement in the lower velocities at the lee separation zone. Wakes et al. (2010) recently compared a 2D numerical model against field data collected at a coastal dune complex at Manson Bay, New Zealand. Although the topography used was simplified to a 2D slice for the purpose of modeling turbulence and roughness parameters on their site they argue that simulations over idealized surface do provide useful results which can give some insights into flow behaviour within such coastal settings.

Important 3D CFD validation work were carried out for wind measurements done at Askervein hill (Salmon et al. 1988) and the earlier comparative computational work performed by Raithby et al. (1987). Kim and Patel (2000) also obtained good agreement between the measured mean wind speed and turbulence kinetic energy results from Askervein hill and those predicted by CFD simulations using a RNG k-ε turbulence model. Their best agreement were found for the windward wind acceleration zone while the biggest discrepancies between the measured and predicted wind characteristics were found in the leeward recirculation zone. Similarly, Castro et al. (2003) performed CFD simulations with the standard k-ε turbulence model and also obtained good agreement of CFD predicted results for the windward zone at Askervein Hill. They attributed the discrepancies between measured and simulated results for the leeward flow regions to the non-constant surface roughness, the limitations of the turbulence model to deal with the anisotropic nature of the turbulence and streamline curvature and transient nature of the flow. Bechmann and Sorensen (2009) performed Hybrid RANS/LES simulations of the Askervein hill wind flows and found improved prediction of the leeward flow anisotropic turbulence characteristics. CFD allows a much more complete spatial coverage of the wind field to be assessed than could be achieved from an instrumental approach. However, field data needed to verify these models is limited, mainly due to operational challenges in collecting appropriate types of data at suitable spatial and temporal resolution for calibration of CFD simulations.

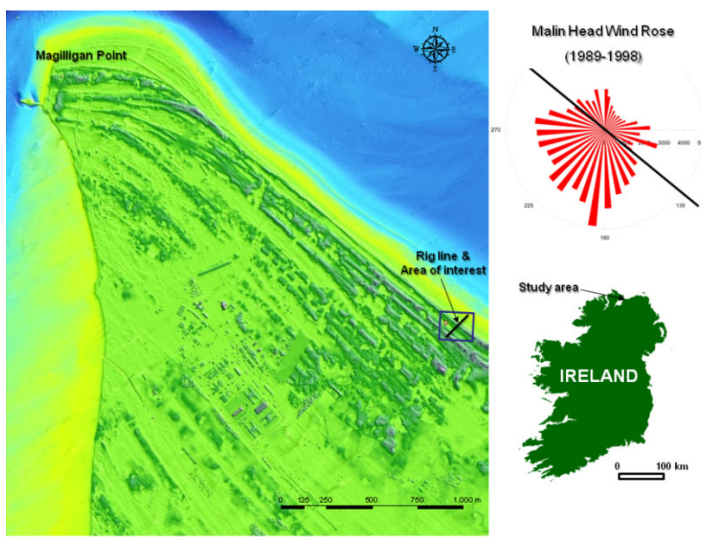

Figure 1: Field test location at Magilligan Strand,

2 FIELD MEASUREMENTS AND CFD SIMULATIONS

2.1 *Site selection and field measurement preparations and instrumentation*

The field experiments took place at Magilligan Strand, Northern Ireland where a range of foredune topographies exists. The strand is part of a 6 km sandy beach system (Jackson *et al*., 2005) extending from Magilligan Point at its northwestern extremity to Benone Strand to the southeast (Figure 1). The wind regime at this location is predominantly offshore. The foredunes at the beach are of sufficient height (up to 11m) to induce significant secondary airflow effects and have been identified in previous work, Lynch et al. (2008, 2009). The beach fronting the dunes is planar and generally unvegetated with little surface debris such as shell lags or wrack lines. Beach and dune sediments consist of uniform, well-sorted, fine-grained quartz sand (mean diameter 0.17mm).

Twenty four ultrasonic anemometers (3D Gill HS-50 model), were configured into a series of vertical arrays to capture vertical and horizontal components of the wind as it flowed over the foredune and across the beach surface (Figure 2). Sensor height locations were first evaluated using a simple CFD run to guide where best to gather flow information. This resulted in elevations ranging from 1m to 16.3m above the local dune/beach surface. The rig line was positioned in a near perpendicular orientation to the coastline. Each sensor had a measurement elevation angle of +/- 50 degrees from the horizontal and U, V, W output was sampled at 50 Hz.

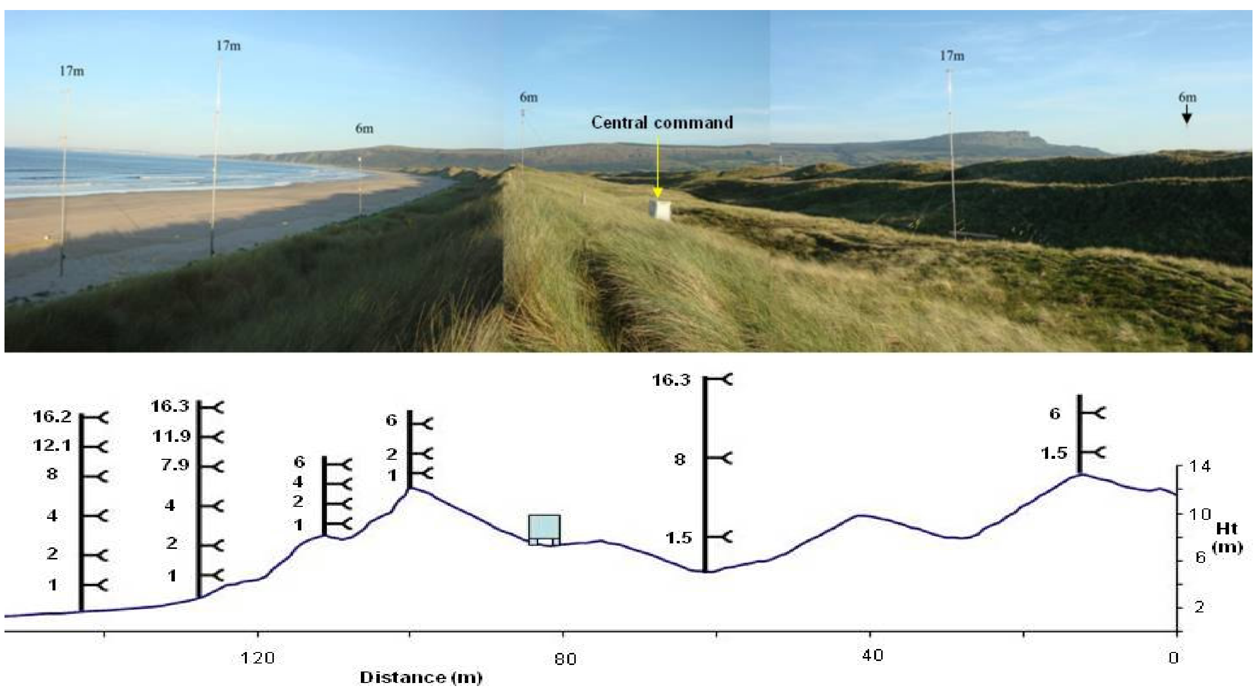

Figure 2: Field measurement site looking towards the south and rake locations with anemometers elevations

2.2 *Field test measurement results and discussion*

A total of 137 hours of wind flow data were collected primarily during offshore wind events. The measurements were taken over a period of time of 11 days, from 23 September to 4 October 2009 and runs were approximately one day long. Misalignments of anemometer orientation in the field were corrected using data rotation as suggested by Walker (2005). For the purpose of comparing results with CFD model results, 10 minute wind speed averages were obtained and binned according to wind direction. Each average record was matched in time with a measurement at a nearby weather station to use as a reference for wind direction and approaching wind speed. For initial comparison of field data with the CFD model results, velocity ratios of sensor speed and reference speed were obtained. The reference speed used was the wind speed taken from the first upwind mast top most sensor (station 1, 6 m height - Figure 2) scaled to gradient height (600m). The standard deviation of the horizontal (u) and vertical (w) wind components were also obtained over the same averaging period for CFD comparison.

2.3 *Topography mapping and computational domain*

A LIDAR survey of the entire Magilligan foreland was completed in June 2008 using a LADS MKII lidar producing surface terrain data corrected to Belfast Lough Datum using observed tides at Green Castle and Londonderry Port (Figure 3). The spatial resolution of the spot data was every 4m with the spheroid ETRF89 and projection UTM, zone 29N, CM 9oW used. A section of coastline measuring approximately 150 m (longshore) x 250 m (cross-shore) was then isolated as the area of interest within which the instrument rig was eventually deployed. To supplement topographic LIDAR mapping, a detailed DGPS survey of this smaller area consisting of more than 48,000 points was also undertaken September to October 2009 using a Trimble 4800 RTK at a point sampling resolution of 1m x 1m. This was particularly important in order to measure any natural topographic changes that may have occurred in the foredune and beach area since the original LIDAR survey. In addition, DGPS data points were gathered along the main frontal foredune ridge crest at a resolution of 0.2m x 0.2m to examine topographic detail on the crestal region. For compatibility, all data from the DGPS surveys were translated into UTM zone 29 and merged with the LIDAR data.

2.4 *Computational fluid dynamics methodology and turbulence model overview*

The simulations performed and presented here were carried out using the open-source CFD software OpenFOAM that solves the system of partial differential equations representing the governing fluid dynamic equations on a three-dimensional computational grid. The details of the general flow solvers are not presented here as it follows standard CFD solution techniques of finite volume discretisation and pressure-velocity coupling. Also, the purpose of the present work is not to evaluate the accuracy of the implementation of the CFD solvers used in OpenFOAM but to evaluate their application and simulation results against measured field test results. The present work evaluated a number of turbulence modeling approaches, the first set applied a steady state Reynolds Averaged Navier Stokes formulation

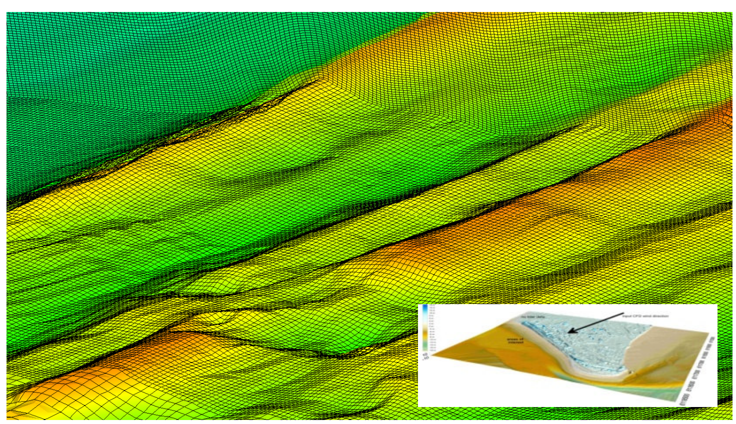

Figure 3: CFD computational mesh with localised mesh refinement near field measurement rake areas. (Insert) LIDAR survey terrain model

using the RANS k-ω SST turbulence model of Menter (1994), the second used a hybrid RANS/LES approach namely IDDES (Improved Delayed Detached Eddy Simulation) of Shur et al (2008) while a third set applied one equation eddy LES. Large Eddy Simulations (LES) can practically resolve turbulence wind flow characteristics far away from terrain surfaces but requires too many grid points near the wall to resolve the near wall turbulence structures. RANS simulation law-of-the-wall turbulence modeling strategies offer a compromise by modeling the near wall turbulence rather the explicitly resolving the flow scales. A combination of both schemes can reduce computational grid counts and are typically classed as Hybrid LES/ RANS or alternatively as Detached Eddy Simulation (DES) models with a variety of scheme to determine when to switch from LES to RANS schemes in the solution domain. A good overview of the development of the hybrid methods and variations to the theme is given by Sparlart (2009) and Fröhlich and Terzi (2008).

Spalart and Almaras (1994) originally developed a one-equation RANS model (SA-RANS) that solves a single transport equation for the eddy viscosity, described in Fröhlich and Terzi (2008). The SA-RANS eddy viscosity transport equation contains a turbulence destruction term that is a function of the wall distance (d). In the subsequent DES approach developed by Spalart et al. (1997), the wall distance was replaced by a length scale dependent on the grid size (Δ) which modifies the SA-RANS model into a LES SGS model. In this SA-DES model the length scale switches between wall distance (RANS) and grid size (LES). The grid length scale used in this model is the maximum of the three dimensional grid spacing instead of the more traditional cube root of the grid volume. One of the disadvantages of earlier DES models was its sensitivity to Grid Induced Separation (GIS) where well-intentioned grid refinement approaches may actually reduced the accuracy of an LES simulation and can produce results less accurate results than traditional RANS simulations on coarser grids, Spalart (2009). Among the strategies to reduce the GIS effect resulted in the Delayed DES (DDES), Spalart (2006) which extends the RANS region by detecting boundary layers, rather than the LES/RANS switching over-simply being a controlled as a function of the wall distance or grid size alone. The resultant modified length scale, as shown in Fröhlich and Terzi (2008) is

$$\widetilde{d} = d - f_d max(0; d - C_{DES}\Delta)$$

where the function f_d was designed to detect and delay the onset of LES near attached boundary layers where the RANS modeling is preferred. The Improved Delayed Detached Eddy Simulation (IDDES) of Shur et al. (2008) is a further derivative of the DDES which combines the above DDES with wall-modeling LES (WMLES) and blends the applied RANS and LES length scales with blending functions as outlined in Shur et al. (2008),

$$\tilde{d}_{hyb} = \tilde{f}_d(1 + f_e)d_{RANS} + \left(1 + \tilde{f}_d\right)C_{DES}\Delta$$

The one equation eddy LES also used here solves a single transport equation for the subgrid-scale turbulent kinetic energy instead of the eddy viscosity. None of the simulations performed with the above mentioned set of turbulence models (k-ω SST, IDDES, LES) accounted for terrain roughness. To improve and evaluate this condition, terrain roughness was applied to the LES simulations only, by including a constant aerodynamic roughness length (z_0) in a law of the wall logarithmic velocity profile that updates the near wall eddy viscosity.

2.5 *Boundary conditions*

Based on a review of the actual surrounding terrain, the approaching wind profile is judges to be similar to flow over open natural terrain. A logarithmic wind velocity profile was used to provide the steady wind speed variation over the height of the domain inlet and also applied as the law of the wall function for the LES-ABL simulations,

$$U(z) = \frac{u_*}{\kappa}\ln\left(\frac{z}{z+z_0}\right)$$

The aerodynamic surface roughness (z_0) and shear velocity (u_*) for all simulations was 0.1m and 0.70m/s, respectively. The inlet turbulence kinetic energy, specific turbulence dissipation rate, eddy viscosity and turbulence intensity profiles used for the various simulations were derived from the turbulence inlet conditions given by Richards and Hoxey (1993)

$$k = \frac{u_*^2}{\sqrt{C_\mu}} \qquad \varepsilon = \frac{u_*^3}{\kappa(z+z_0)} \qquad \omega = \frac{\varepsilon}{C_\mu k} \qquad \nu_t = \frac{k}{\omega} \qquad I_u = \frac{\sqrt{\frac{2}{3}k}}{U(z)}$$

3 COMPARISON BETWEEN MEASURED AND SIMULATED WIND PROFILES

Two simulations cases were simulated for winds approaching from 217° (Case 1) and from 270° (Case2), and results compared against measured results binned to the same wind directions.

3.1.1 *Results comparison for Case 1 and Case 2*

The Case 1 LES-ABL and RANS simulations resolved the expected wind recirculation zone leeward of the foredune/beach interface (Figure 6 top images). The LES-ABL simulations predict lower near surface velocities compared to the RANS simulation, due to the RANS model absence of wall roughness treatment and its inability to capture localised recirculation in depressions and valleys (between masts 1 and 3) along the rake line (Figure 6, bottom images). The mean horizontal velocity profile comparison for case 1 at each rake position is shown in Figure 4. As expected, all simulations performed without accounting for terrain roughness, did not agree well with the measurements and tend to overpredict the near surface velocity. The results for the one-equation LES-ABL simulations agree favourably with field measurements for all 6 mast locations, including the recirculation zones captured by masts 5 and 6 (Figure 4). The LES-ABL simulated results of the standard deviation of the mean horizontal velocity compares favourably for most masts and, perhaps remarkably, also for masts 5 and 6, in the recirculation zone. Future simulations would be performed and compared agains this set using the IDDES with the terrain roughness modeling. The RANS and LES-ABL simulations shown here suggest the recirculation zone reattachment location at approximately four to five times the foredune height above the beach. For the Case 1 wind flows, no coherent terrain wind steering is predicted and instead localised recirculation zones, that are not two-dimensional, are predicted along the beach/foredune system.

The Case 2 LES-ABL simulations predict smaller localised recirculation zones along the rake line, including a small recirculation zone at the foredune/beach location, isolated to the top of the dune (Figure 7). The Case 2 RANS simulation did not predict any recirculation along the rake line.The dunes system and their alignement to the prevailing west winds are responsible for localised steering of the wind toward the southeast as can be seen in Figure 6, showing the velocity vectors in a plane 2 m above the terrain. Both the LES-ABL and RANS simulations capture the near surface wind steering towards the south-east, the LES simulations are just predicting lower velocities due to inclusion of terrain roughness and its likely better resolution of near surfaces eddies. Figure 5 shows the CFD and field test mean wind velocity profile comparison. Again these results shows that the LES-ABL simulations agree favourable with the measured results for all mast locations while the simulations performed without aerodynamic roughness does not agree well.

4 CONCLUSION AND FUTURE WORK

The present work describes the first results from field tests measurements and comparative CFD simulations done to evaluate the off-shore wind flow over complex dune terrain at Magilligan. The measured results show good comparison with the LES simulations as long as the aerodynamic roughness of the terrain is included in the modeling approach. The favourable agreement obtained using the LES-ABL approach suggests that the CFD method can be used to examine the influences of the terrain in locally steering the wind conditions, an important aspect driving the Aeolian sand transport at the site. Also, the LES-ABL results suggest that the method can help identify the recirculation zone location and the localised near surface wind velocity and turbulence intensity. Obtaining such data can help identify the required windward wind characteristic to initiate sand transport either in a reciculation zone or parallel to the beach dunes during wind steering conditions. More work will be performed to evaluate the performance of IDDES simulation method with the ABL aerodynamic roughness treatment at the terrain boundary. The unique opportunity offered by this research program to numerically predict and validate wind flows over complex terrain such as dune systems, may present valuable new tools and insight for the computational wind engineering and geomorphology research community.

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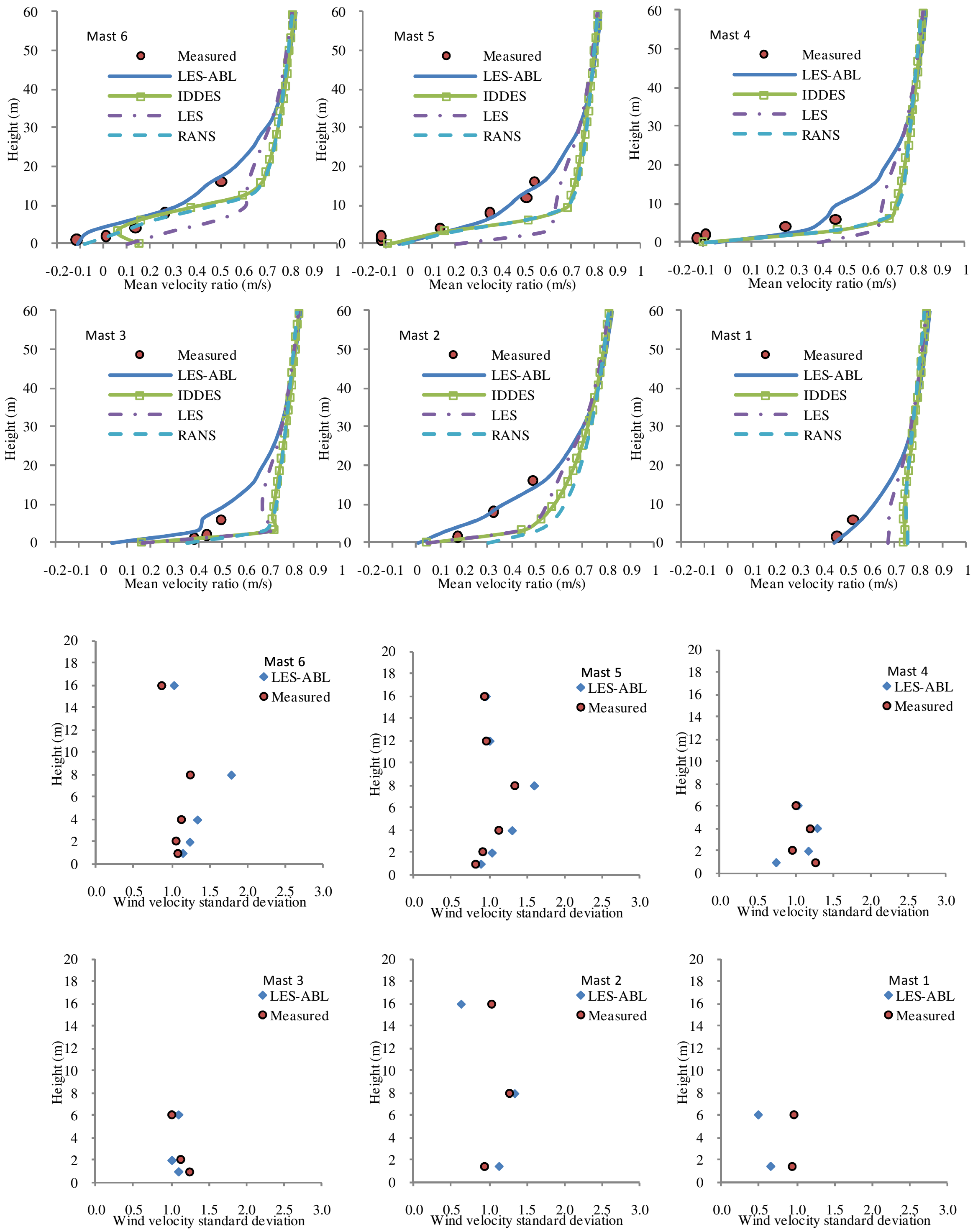

Figure 4: Case 1 measured and CFD mean velocity ratio and standard deviation profiles (Masts 1-6)

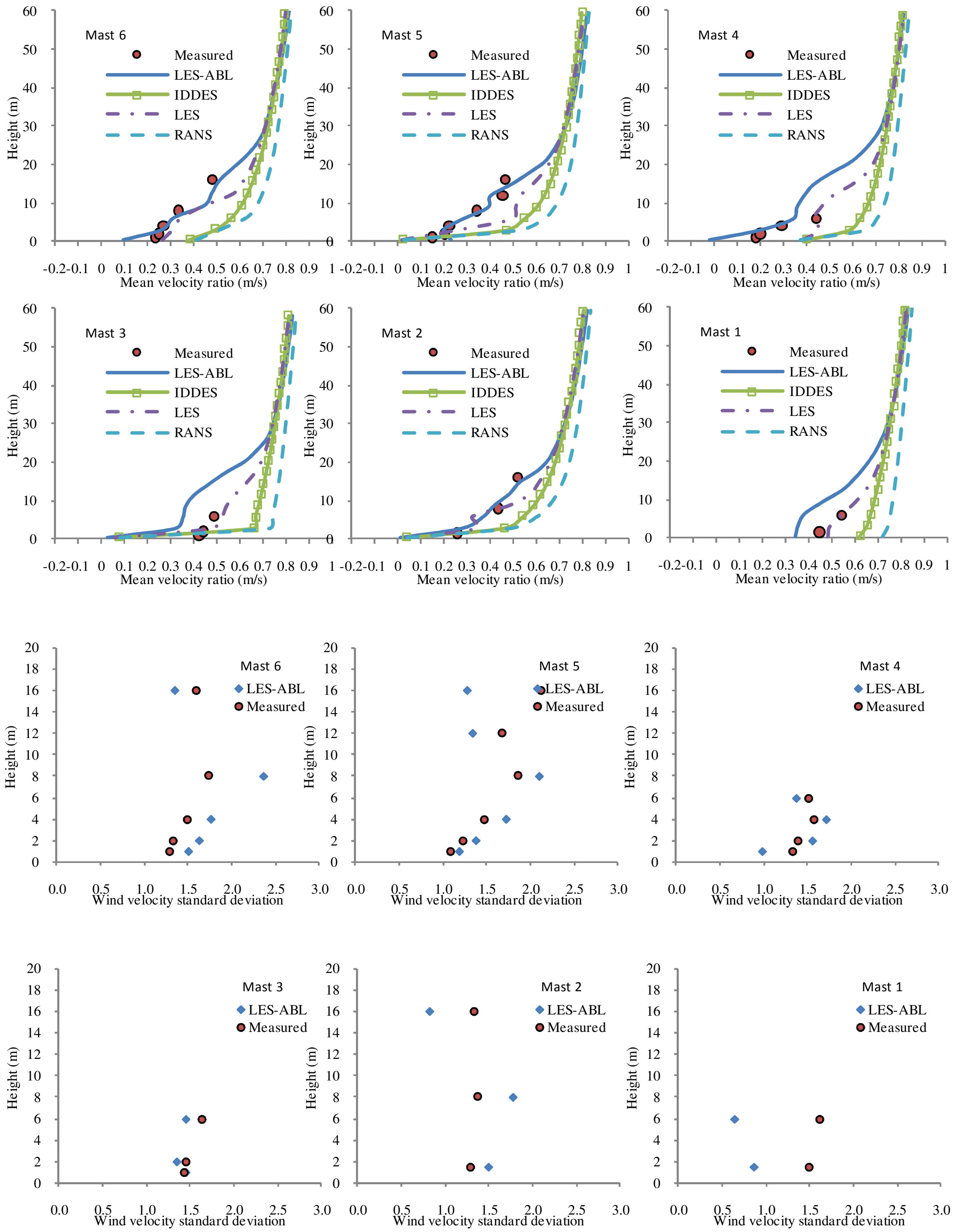

Figure 5: Case 2 measured and CFD mean velocity ratio and standard deviation profiles (Masts 1-6)

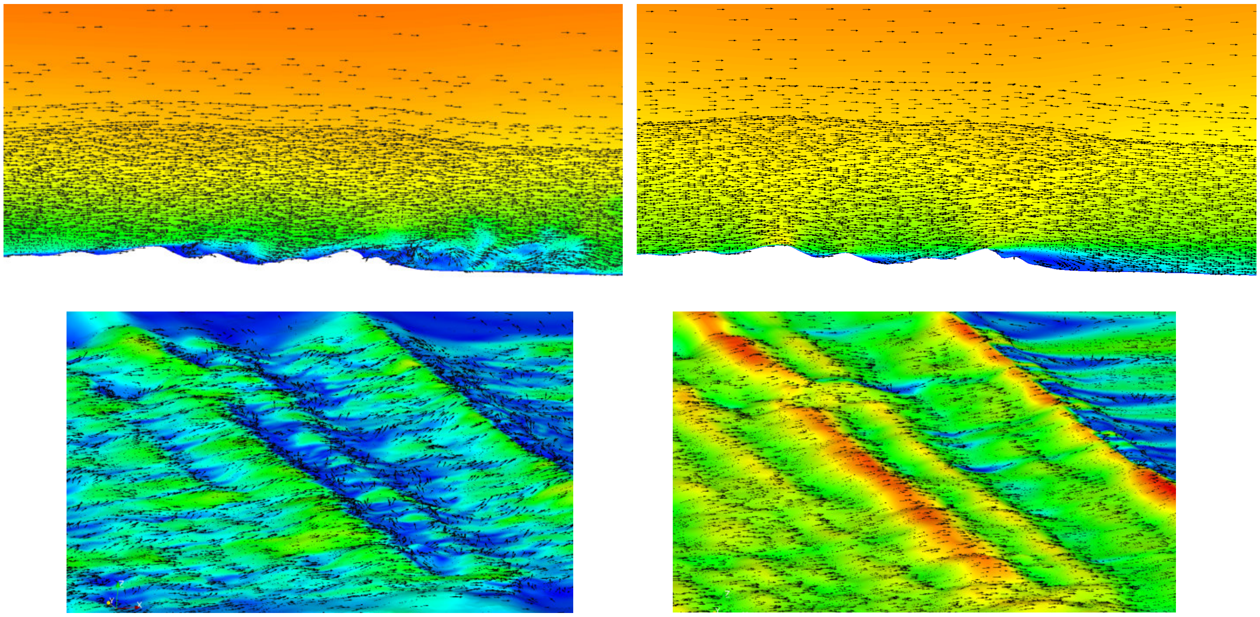

Figure 6: Case 1 velocity vectors and contours for a vertical plane throught the rake line (top) and at 2m above the terrain (bottom). Left images:LES – ABL, Right images: k-ω SST

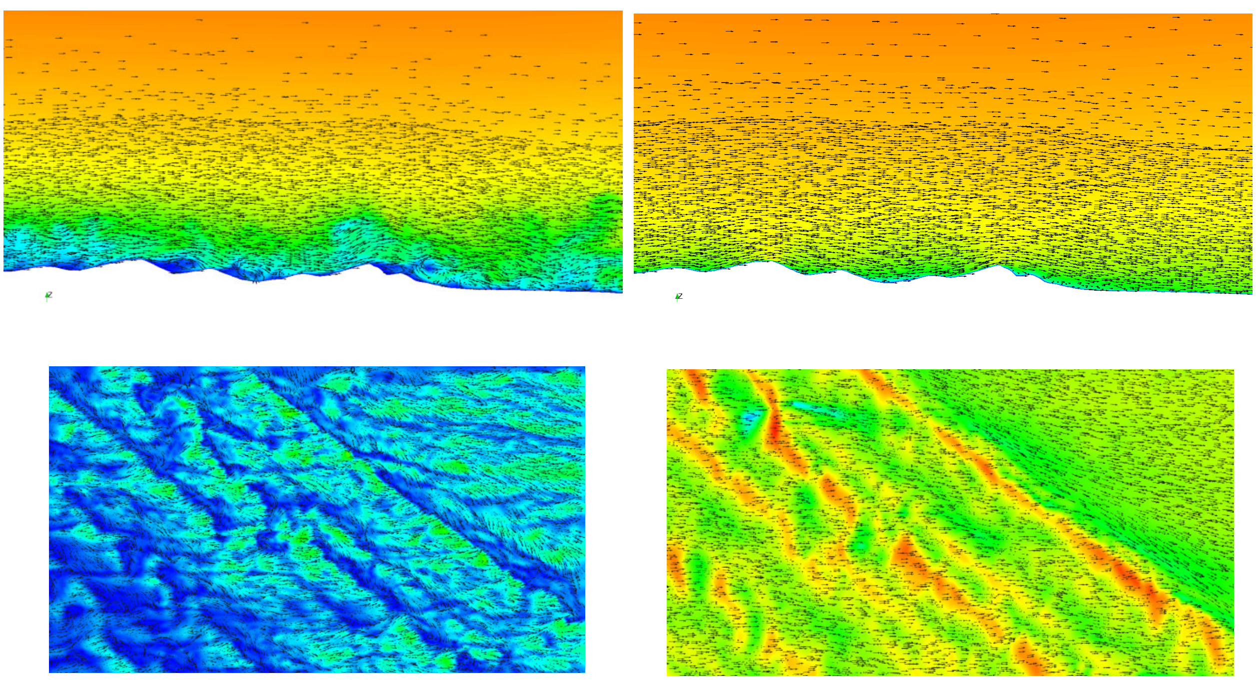

Figure 7: Case 2 velocity vectors and contours for a vertical plane throught the rake line (top) and at 2m above the terrain (bottom). Left images:LES – ABL, Right images: k-ω SST